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Design and Construction of a Nuclear Powered Milliwatt Generator

J. H. Birden, K. C. Jordan and M. L. Miller

April 6, 1973

ATOMIC ENERGY COMMISSION • UNITED STATES OF AMERICA •

AEC Research and Development Report

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Miamisburg, Ohio
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DISCLAIMER

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ABSTRACT

A ^{238}Pu powered thermoelectric milliwatt generator of very rugged design is described. The open circuit voltage is 12 V. With an optimum load of 16,500 ohms, the power output is 2.2 mW at 6 V. The ^{238}Pu source supplies heat to an 1170 junction thermopile made of Tophel Special-Cupron Special wire. A thermopile fabrication technique is described. The multiple hermetically sealed unit is a right cylinder, 2.350 in. (5.969 cm) o.d. x 2.125 in. (5.398 cm) high, which weighs 3/4 lb (300 g). Only 7.8 mR/hr of gamma and 10.9 n/cm^2/sec are emitted at the surface. An electrical analogue of the thermal circuit is included.

INTRODUCTION

The original work on thermoelectric generators at Mound Laboratory was started in 1954. In 1954 two patent applications were filed, and subsequently granted,[1,2] for batteries using radioactive decay as the heat source and thermoelectricity for the generator. The design formula was developed and checked against prototypes in 1958.[3] The discovery of high-temperature polonides and the increased availability of ^{238}Pu, ^{242}Cm, and ^{244}Cm greatly expanded the applications for radioisotope heat sources.

In early 1963 the Atomic Energy Commission solicited bids on a radioisotope-powered milliwatt generator. Sandia/Albuquerque sought bids within the AEC, while other AEC agencies sought bids from private industry. Design specifications are given in Table 1. Mound Laboratory received the contract from the Sandia Corporation for the design, testing, and production of about 40 generators. These contracts extended from early 1963 through 1965.

Table 1

DESIGN SPECIFICATIONS

Electrical Output:	the voltage shall be continuous and remain between a minimum of 3 V and a maximum of 4.5 V; approximately 1 mW output.	
Weight:	less than 1 lb.	
Operating Lifetime:	40,000 hr minimum.	
Ambient Environmental Conditions:		
	Temperature:	Shock from -65°F to +165°F; three 8-hr cycles with 4 hr at each extreme.
	Shock:	100 g, 1/2 sine pulse of 10 msec duration, three in each direction along the three major mutually perpendicular axes of the device (total of 18 shocks).
	Vibration:	10 g maximum (maximum component response of 20 g), sine wave from 10 to 2,000 cps in each of the three mutually perpendicular axes.
	Radiation:	1,000 R during operating life with short time exposure of the power supply to 100 R.
	Humidity:	93 %, ten consecutive 48-hr cycles from 68 to 149°F.
	Pressure:	2.13 in. Hg for 8 hr at -80°F, 70 in. Hg for 1 hr.
Fuel:	Plutonium-238	
Reliability:	The final design shall be based on considerations of utmost reliability such that a failure rate of 1 in 1000 units during the operating life, with a 0.90 confidence level, may be achieved in future production units.	

DESCRIPTION OF GENERATOR

Basically the milliwatt generator is an isotope-powered thermopile which resembles a cartwheel in construction (see Figures 1 and 2). The heat source is at the hub with the spoke-like mica cards terminating at the rim. The thermopiles are mounted on the mica cards. The hot junctions are bonded to the heat source, and the cold junctions are clamped in their bar-type heat sink. The heat source, wholly supported by the mica card thermopiles, is doubly contained plutonium-238 metal.

Heat Source Plutonium-238 metal was selected as the radioactive isotope for the heat source. It has a half-life of 88.4 yr and a specific power of 0.45 W/g (based on 80% ^{238}Pu in the metal).[4] Tantalum was chosen as the material for the inner container because of its favorable compatibility with plutonium metal at the operating temperature of the heat source. The outer container, or strength member, was constructed of Haynes alloy No. 25. A thin coat (0.0005 in.) of ferric oxide (Fe_2O_3) was vapor deposited on the cylindrical outside surface prior to welding to provide electrical insulation for the hot junctions.

Mica Card Thermopiles New fabrication techniques were required to produce these units in quantity with high reliability. The thermocouple junctions are made of Tophel Special and Cupron Special* wire. The small hole pattern in the mica card increases the thermal resistance from hot to cold junctions. Each mica card has 90 ± 1 hot junctions. There are 13 mica cards in each generator.

The Cage The cold junction clamping bars plus the two end rings make up the cage. These aluminum parts are anodized after machining.

The Outer Case The outer case was made of 300 series stainless steel. The top plate contains three integral terminals and one mounting lug.

CONSTRUCTION OF MICA CARD THERMOPILES

The physical characteristics of sheet mica provide the high degree of shock and vibration resistance inherent in this design. Its particular combination of high electrical resistance, low thermal conductivity, and ease of fabrication makes it ideal for this application. The thermocouple junctions are made of Tophel Special-Cupron Special wire, which is 0.0018 in. (0.0046 cm) o.d. These alloys are similar to chromel p-constantan; further information is given in Appendix A. The linear junction density was 120 per inch. Each junction occupies about 0.004 in. (0.010 cm) with a similar spacing.

Card Preparation The mica cards were purchased to size (1 x 3 x 0.0035-0.0040 in.) (2.5 x 7.6 x 0.0089-0.0102 cm). Figure 3 shows the successive preparation steps. First two reference holes are punched with a jig. The next step is to grind the 1 in. width down to 0.750 in.

*Wilbur B. Driver Company, Newark, New Jersey.

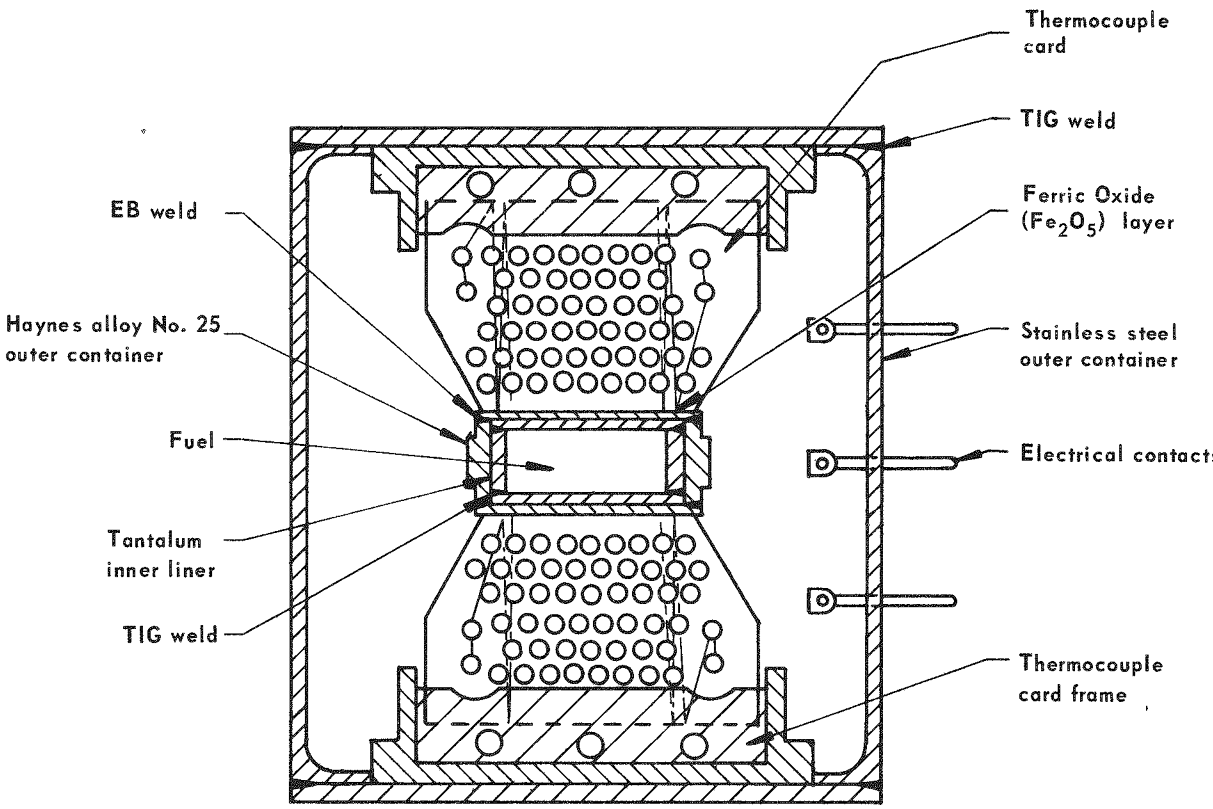


FIGURE 1 - Schematic diagram of generator.

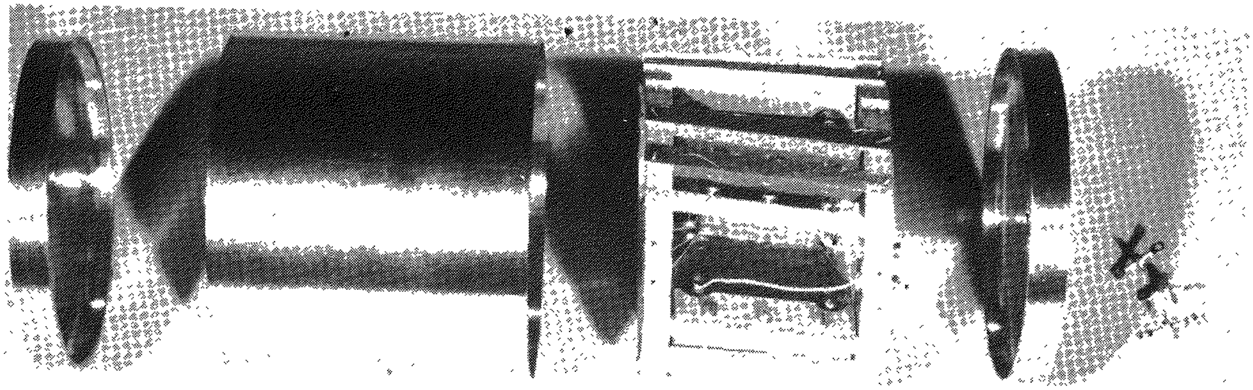


FIGURE 2 - Exploded view of early generator.

(1.915 cm). Then several mica cards are clamped in a sizing jig, and ground down by hand on a tool maker surface plate (Figure 4), starting with coarse carborundum cloth and finishing with 600 mesh wet or dry carborundum paper. Sharp, right-angle edges, free of scratches and burrs are necessary. The next step is to punch the small hole pattern which increases the thermal resistance from hot to cold junctions (across the 0.750 in. width). Only one card is punched at a time; punching multiple cards introduces radial cracks in the mica. The punch must be kept sharp to produce clean holes, free of burrs and radial cracks, to permit the cards to pass the vibration tests successfully.

<u>Applying Thermocouple Wire</u> Two cards are handmounted on opposite sides of a mandrel and held there by small, screw-attached clamps until the card is adjusted. A scribed line on the mandrel is centered in either of the two locating holes. Approximately 0.005 in. of each edge of the card extends beyond the edge of the mandrel, which is slightly under 3/4 in. in width. (See Figure 5)

The wire is now wound upon the card-mandrel assembly using a special fixture on a lathe (Figure 6). It is preferable that the Tophel Special wire be wound first so that, when the junctions are formed, the electron beam can approach the higher melting Tophel Special first. The wire is passed from a spool through a hypodermic needle and taped to the mandrel now in place on the lathe. With the lathe speed at 20 rpm, this wire is wound at 120 turns/in. for a length of about 1 in. It is cut, and the free end of the wire is also taped to the mandrel.

The procedure for winding the Cupron Special wire is considerably more complex, and additional equipment must be used in conjunction with the lathe. A small electromagnet is mounted on the side of the tool holder; its shaped pole pieces are extended in near proximity to the hypodermic needle. A soft iron armature is attached to the side of the hypodermic needle completing the magnetic circuit; the armature is faced with a

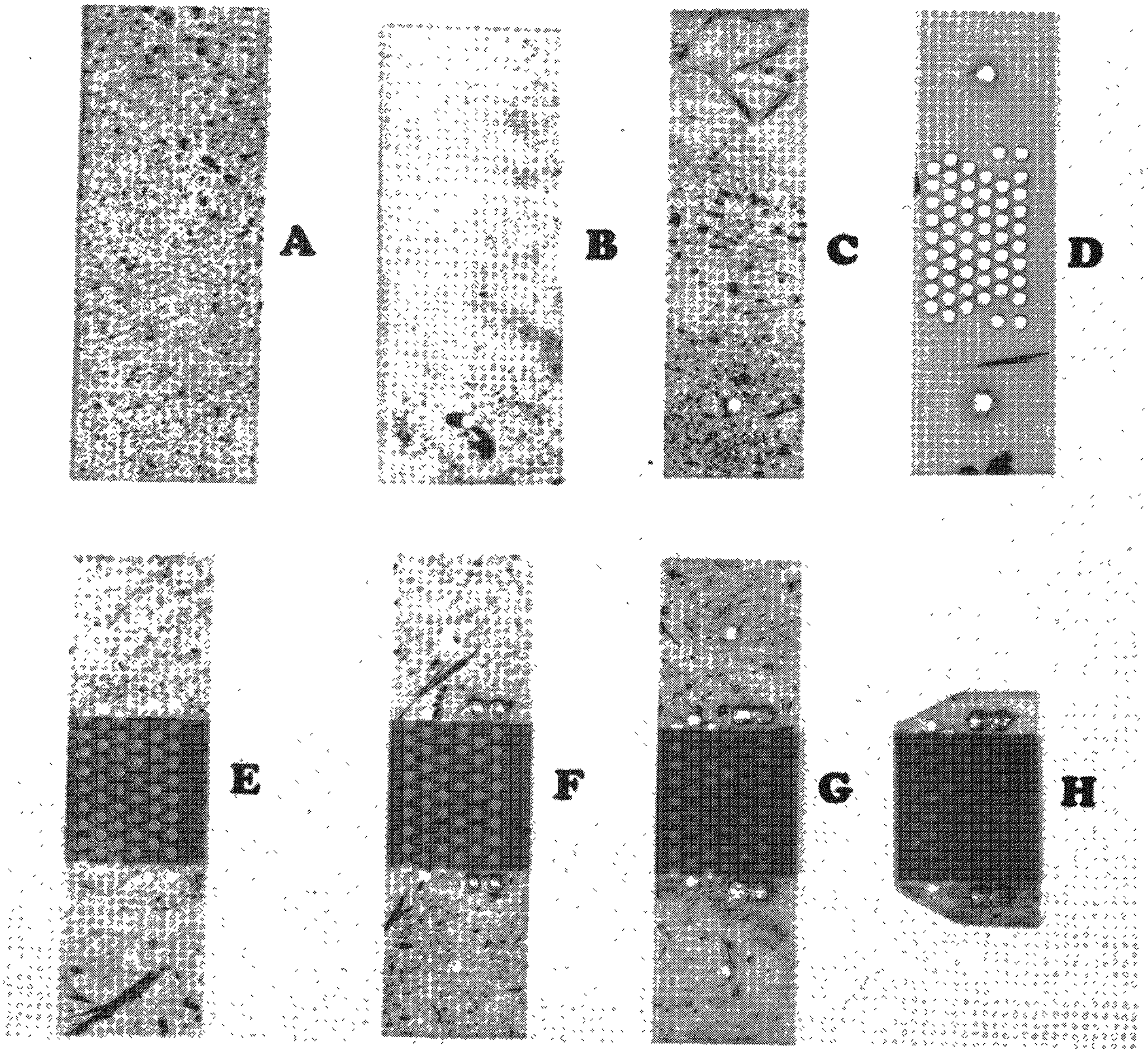


FIGURE 3 - Steps in fabrication of mica card thermopile. A. Mica card as purchased. B. Reference holes punched. C. Edges ground to 0.70 in. width. D. Small hole pattern punched. E. Wires applied (excess removed). F. Wiring grommets installed. G. Wires soldered in place. H. Completed thermopile.

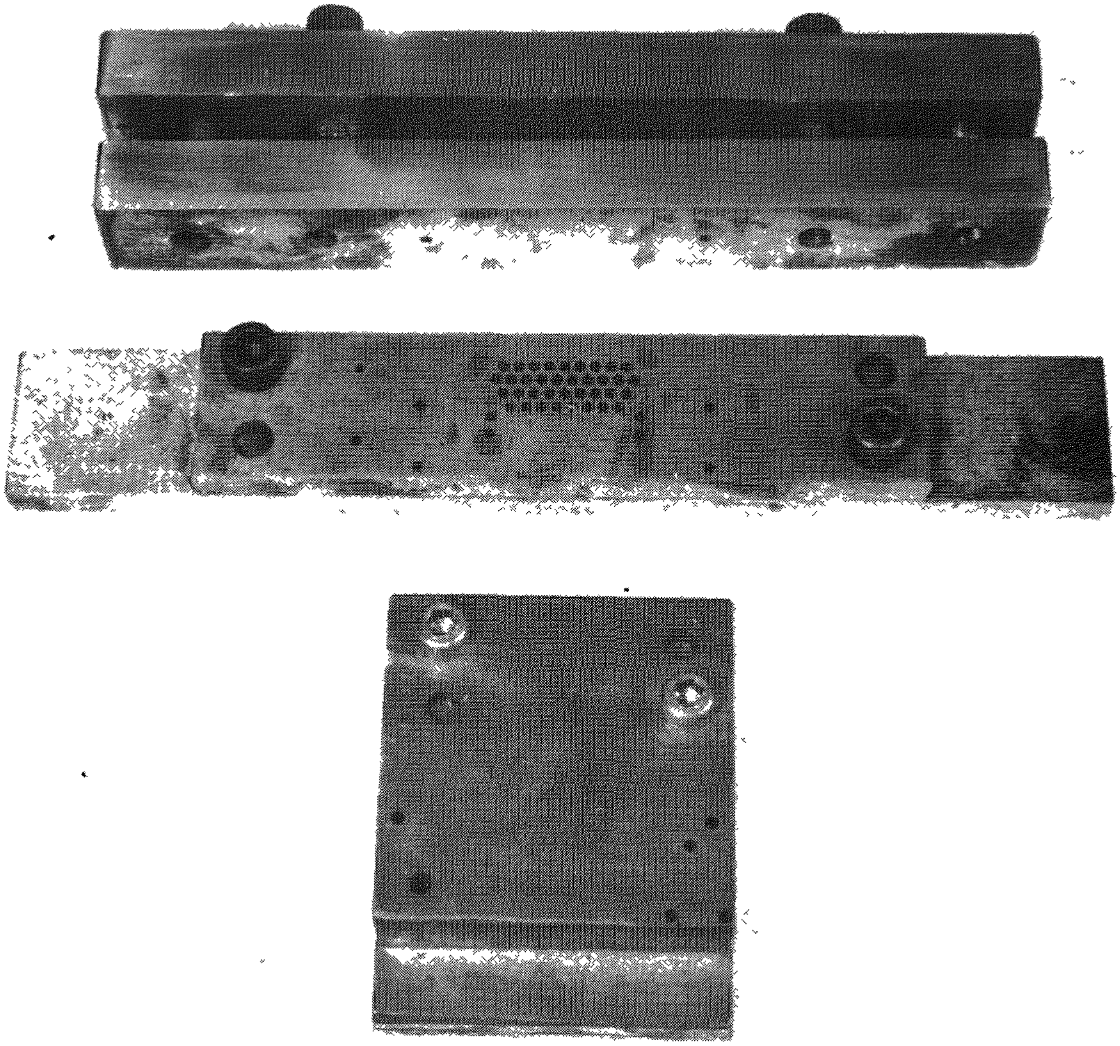


FIGURE 4 - Mica card fabrication jigs.

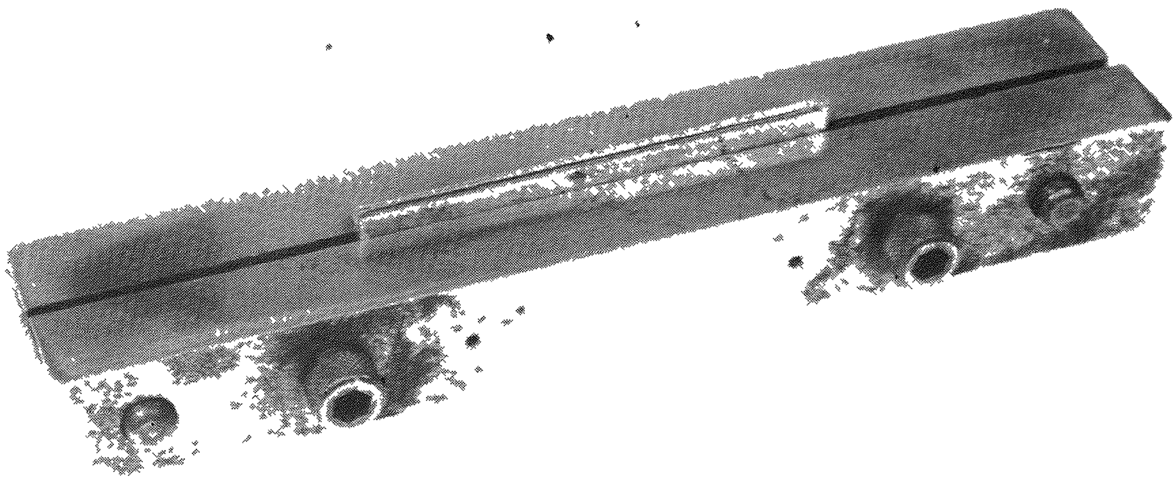


FIGURE 5 - Mica cards in width sizing jig before grinding.

thin piece of aluminum foil to prevent magnetic sticking. The electromagnet is energized through a microswitch which is activated by a camming ring mounted on the lathe spindle. Each of the two cams turns the microswitch on for 90° of each 180° of rotation, specifically between 80° and 170°. This on-off of the electromagnet controls the position of the needle, and thus the Cupron Special wire can be wound in a zig zag manner between the turns of the Tophel Special wire. The Cupron Special wire is taped to the mandrel so that winding will proceed in the same direction as the first wire. With the power supply turned off, the lathe compound is adjusted so that the Cupron Special wire touches the Tophel Special to the left of the first turn. With the power supply turned on, the microswitch shorted, and the lathe advanced 90°, the power supply voltage is adjusted until the Cupron Special wire touches the Tophel Special to the right of the first advanced turn. With the microswitch by-pass removed, the lathe is stopped immediately before the Cupron Special wire touches the leading edge of either of the mica cards, and then the camming ring is adjusted until the microswitch has just turned off. With these adjustments completed, the Cupron Special wire is wound at 120 turns/in. and a lathe speed of 20 rpm.

Figure 7 illustrates the manner in which the cards are wound. Several preliminary turns are made with the microswitch shorted. Then as the leading edge of the mica card approaches, the electromagnet is off and

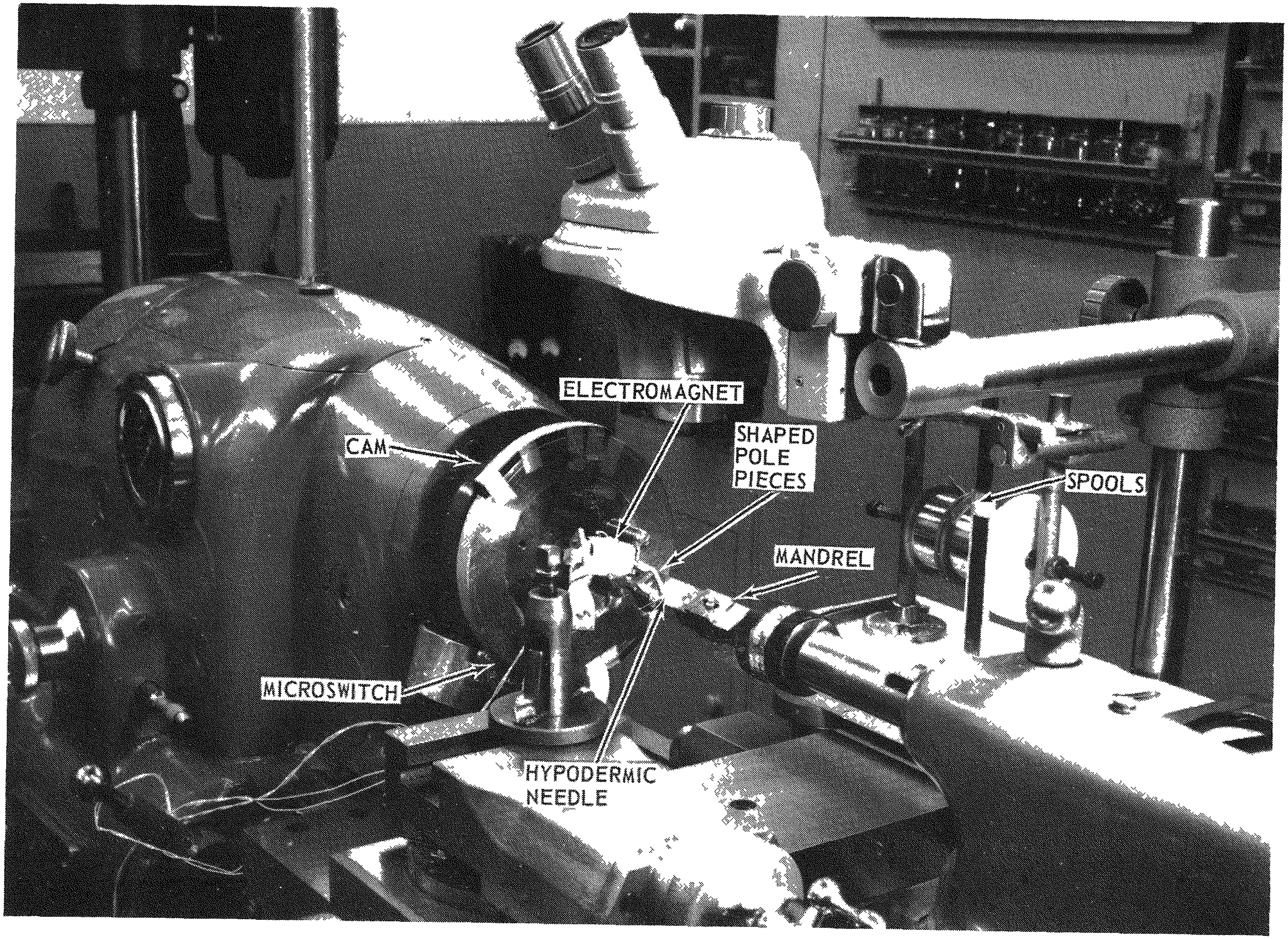


FIGURE 6 - Lathe with special fixture for winding thermocouple wire on mica cards.

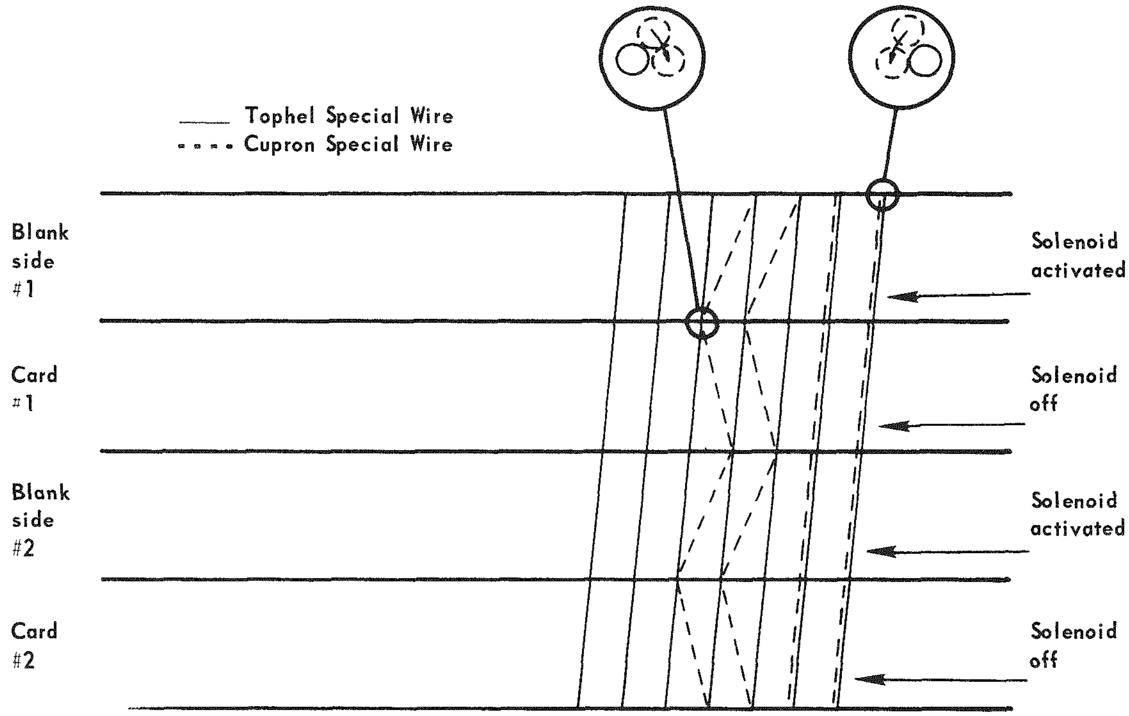


FIGURE 7 - Diagram illustrating the winding of the thermocouple wires. The four sides of the Mandrel are shown.

the Cupron Special is laid down to the left and touching the Tophel Special. As the trailing edge of the mica card is approached, the cam activates the microswitch, the electromagnet pulls the needle to the left, and the Cupron Special is laid down to the right and touching the next advanced turn of Tophel Special. Just before touching the leading edge of the second mica card, the needle relaxes ready to repeat the cycle for the second card. The second wire is also wound at 120 turns/in. This wire is cut and the free end is taped to the mandrel.

The mandrel is now removed from the lathe and the windings are inspected for crossed or separated wires. Corrections are made by uncrossing crossed wires and joining separated ones; a scalpel point or small probe is used to make these corrections.

<u>Forming the Junctions</u> The wires are lightly painted with a dilute solution of Glyptal #1202 varnish to hold the wires in place after the junctions are formed. A back up plate is installed over the mica cards to dimensionally stabilize the edge of the cards during the welding operation. Two strips of masking tape are placed over the wires on the two remaining sides of the mandrel. After the junctions are formed, this wire becomes scrap.

The prepared mandrel is placed on the X-Y table in the vacuum chamber of the electron beam welder. The mandrel is adjusted so the mica cards are parallel to both the X axis and the path of the electron beam. The beam parameters are 25000 V at 0.0008 A. The effective beam diameter is adjusted to 0.015 in. (0.038 cm) as determined by a melted slot in 0.00025 in. (0.00064 cm) thick 302 stainless steel foil.

The center of the beam is positioned approximately 0.040 in. (0.102 cm) from the inside edge of the mica card. As the table traverses the X axis under the beam (at ~1 in./sec), the thermocouple pairs are melted through and simultaneously welded together, forming each junction separately. Without changing beam position, a second pass generally improves the shape of the junctions (See Figure 8). The welding sequence is performed four times for each mandrel (two thermocouple cards).

Completing the Thermopile Card The mandrel is taken from the vacuum chamber and the two thermopiles are carefully removed from the mandrel. The excess junctions are removed, wiring grommets are installed, and the end wires are soldered in place. The hot junctions are warmed while the output is read by a voltmeter, and the polarity is marked on the mica. The junctions bend around the edge of the mica card at a right angle as it comes off the winding mandrel. The cold junctions must be straightened before they are clamped in the cold bar. The cold junctions are straightened in a jig and the excess mica is cut off with a scalpel. Other cutting procedures produced undesirable edge cracks in the mica. Each completed thermopile card has 90 ± 1 hot junctions. All thermocouples in the generator are connected in series, adding to a total of 1170 ± 13.

Each thermopile is mounted loosely in a cold bar heat sink assembly, for storage until used. Good heat transfer from the cold junctions and excellent electrical insulation are provided by the folded 0.003 in. (0.008 cm) thick Teflon strip when clamped tightly in the anodized cold bar during final assembly (See Figure 9).

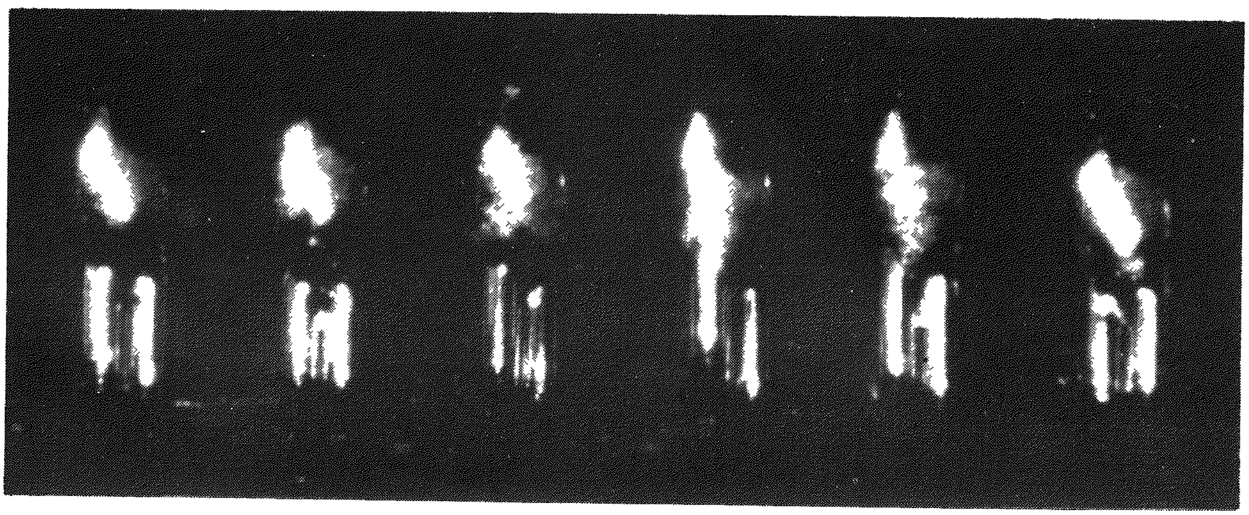


FIGURE 8 - Tophel Special - Cupron Special welded junctions.

ASSEMBLY OF THE GENERATOR

The Assembly of the Cage, Thermopile Cards, and Heat Source The cage end-rings are prespaced by three empty cold bars. The Lucite end pieces with axial rods are mounted axially in the ends to center the heat source and to act as a heat sink.

With the heat source in place, the mica card thermopile, with the cold bar lightly clamped, is put into place with the hot junctions lightly touching the coated heat source. Two 0-80 fillister head screws are required to mount each cold bar. While the thermopile is centered and lightly touching the heat source, the cold junctions are permanently clamped. A thin bead of thick AI Polymer* is laid along each side of the hot junctions to provide a low thermal resistance path and to anchor the heat source. Figure 10 shows a generator partially assembled. The rest of the cards are mounted and the voltage output of each card is compared. All cards should read within ±3% of the average voltage. If acceptable, the thermopiles are wired in series to provide the total output, and the output leads are attached.

The plastic end mounts are replaced by the lathe mounting adaptor. Strips of masking tape prevent lathe turnings from entering the cage assembly. The diameter is turned to a close fit with the outer container and cleaned; the tape and lathe mount are removed.

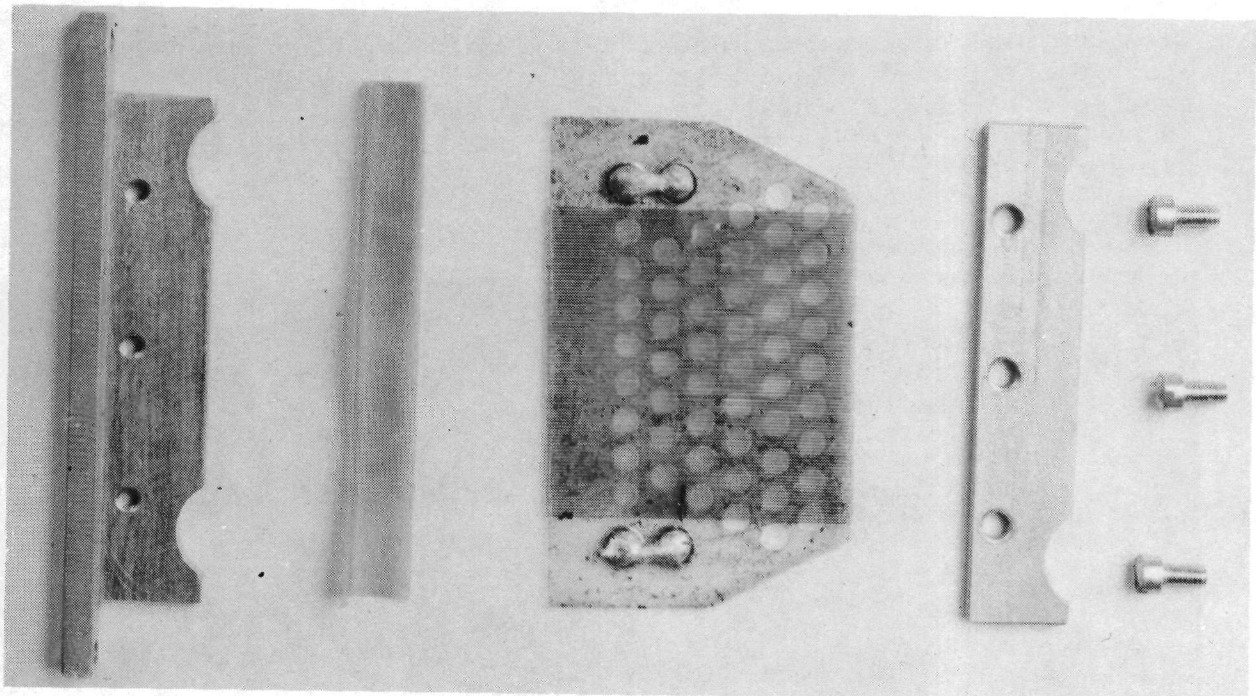


FIGURE 9 - Exploded view of mica card thermopile and cold junction clamp, and heat sink assembly.

*Amoco Chemical Co., 130 E. Randolph Dr., Chicago, Ill.

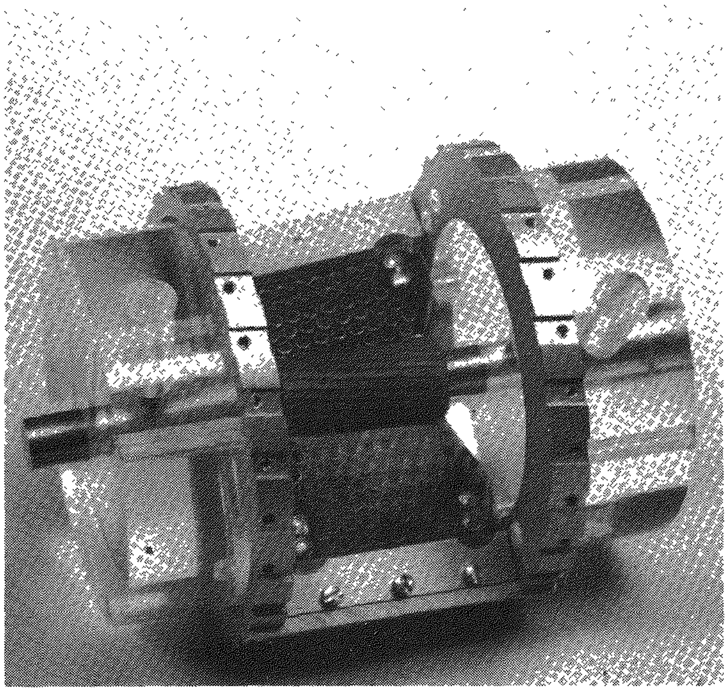


FIGURE 10 - Partial assembly of generator

Assembly of the Major Mechanical Components The major mechanical components of the generator consist of the generator cage, which is a close fit into the outer sleeve, and the two end plates, one of which carries the electrical feed-through terminals. Both end plates are TIG welded. The welded sleeve and bottom-plate unit and the terminal-plate unit are helium leak tested before final assembly. A photograph of the outer case is shown in Figure 11.

The cage assembly is slipped into the outer case and AI Polymer is lightly dressed along the sides of each cold bar to provide a low thermal resistance path to the outer case. The AI Polymer must be thoroughly baked to remove excess solvent. The Teflon-insulated output leads are attached to the header terminals, but the header plate is not put in place until final assembly in the dry box. The wire leads must be firmly attached mechanically to prevent an open circuit occurring during the final high temperature TIG welding and soldering operations.

TIG Welding Operation An adjustable TIG welding head and jig rotator with speed control, and a small vibration stand are mounted in the dry box. After all generator parts are introduced into the dry box and a 100% argon atmosphere has been established, the generator unit is set on the vibration stand and slowly filled with opacified Santocel® (see Appendix B). Overfilling and packing are necessary to pass the voltage output requirements during vibration testing. Optimum packing density for maximum output was not determined.

The terminal header is pushed into place and sealed flush with the end of the case. All excess Santocel is removed. The generator is clamped in a multisegmented cooling block and mounted in the jig rotator. The generator protrudes above the cooling block 0.031 in. (0.079 cm). The welding parameters are:

- Arc gap is 0.035 in. (0.089 cm).
- Electrode is 0.062 in. (0.157 cm) o.d. thoriated tungsten rod with its point ground to a 90° included angle.

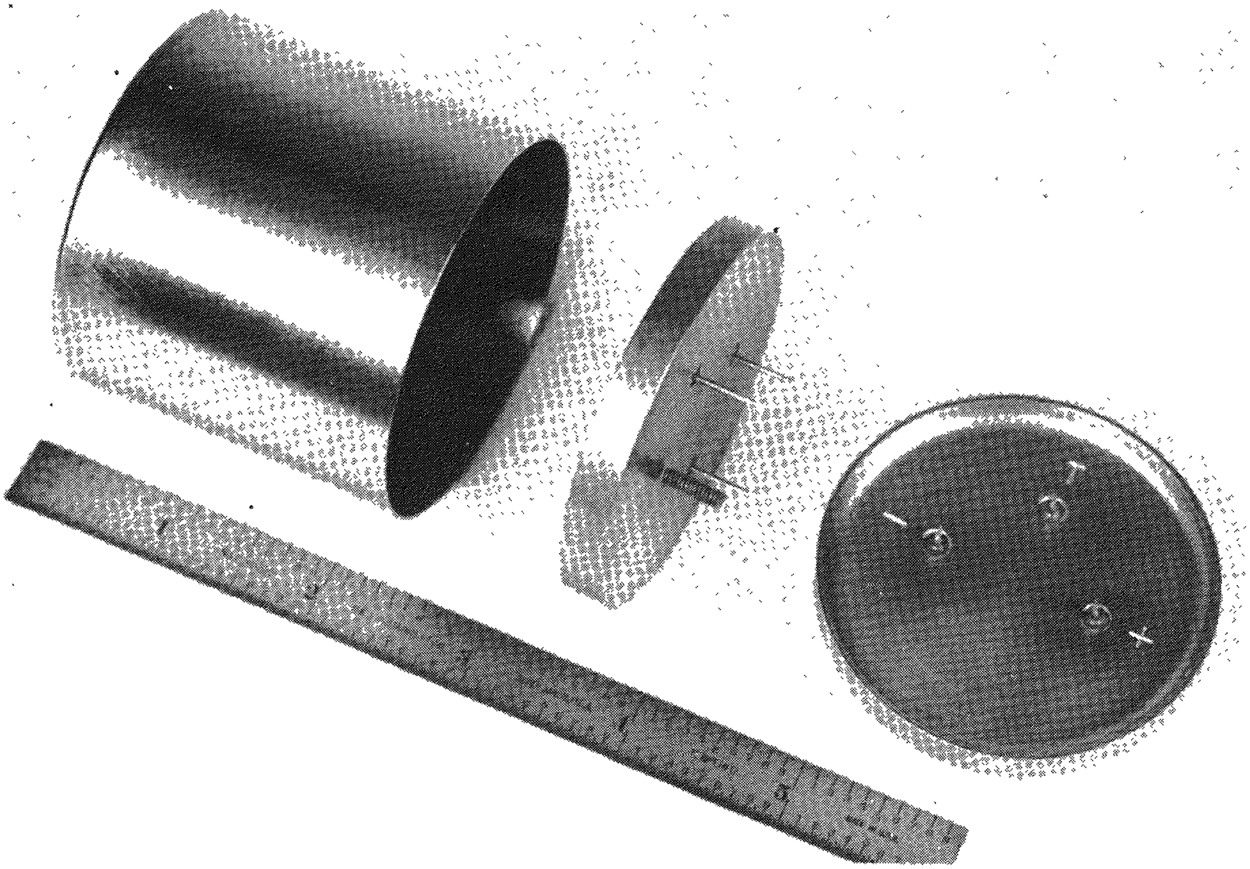


FIGURE 11 - Outer case of last prototype generator.

- Argon flow rate to welding head is 15 ft^3/hr (118 cm^3/sec).
- Linear welding speed is 13.53 in./min (0.573 cm/sec) or 32 sec per revolution for this generator.
- Welding current is 35 A.

The electrode is positioned vertically over the weld seam. Three tack welds, 120° apart, are made. Continuing from the last tack weld, a 95% pass is made. After the internal pressure has equilibrated and cooling has started, the final closure is made and the current is tapered off to zero. This procedure prevents blow holes from developing due to internal pressure build-up.

TESTS AND EVALUATIONS

In general, all inspection procedures were made immediately after the operation was completed.

Heat Source All welds were helium leak tested and radiographed. Sample welds made before and after each production weld were metallographically examined at 120X magnification.

Samples of both inner and outer capsules were internally pressured to destruction at 25°C. The minimum burst pressure was 25,000 psi for the outer container and 5000 psi for the inner container. One completely welded assembly of inner and outer containers burst at 32,000 psi. A photograph of this burst capsule is shown in Figure 12. In all the pressure tests, the breaks occurred in the center of the cylindrical wall section.

Leak Testing Since the generator contains 100 % argon gas, the outer case was leak tested with an argon leak detector. Anything less than 1×10^{-7} cc/sec STP was accepted. The heat source inner and outer capsules were leak tested with a helium leak detector. Anything less than 1×10^{-7} cc/sec STP was accepted.

Electrical Tests and Calculations

Leakage Resistances All leakage resistances between thermopiles on cards, thermopile and cold bar, thermopile and heat source, electrical terminals and case, and Teflon feed through terminals and frame were measured with a vacuum tube voltmeter (RCA WV98C) on the RX 1,000,000 resistance scale. The minimum acceptable resistance was 1×10^9 ohms.

Electrical Output All potentials should be measured with a high input impedance voltmeter. For 0.1 percent loading error the voltmeter must have 1000 times the internal resistance of the generator (16,500 Ω) or 16.5 megohms. This can be accomplished by a null type potentiometer system or some digital voltmeters.

The open circuit generator voltage V_o as shown in Figure 13 can be measured as well as the voltage drop across a decade box R_L as load.

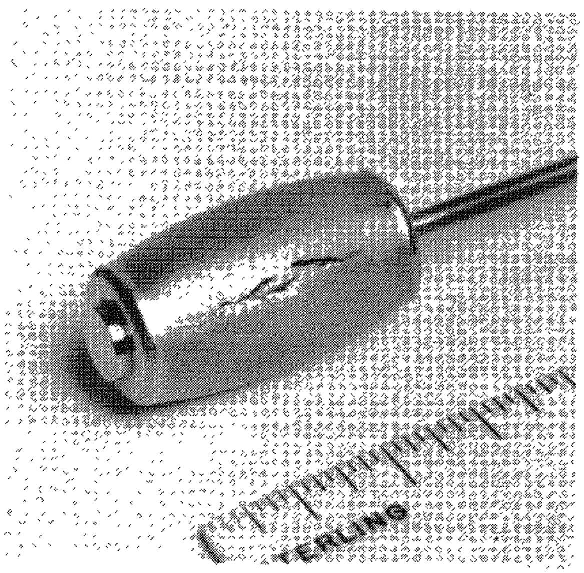
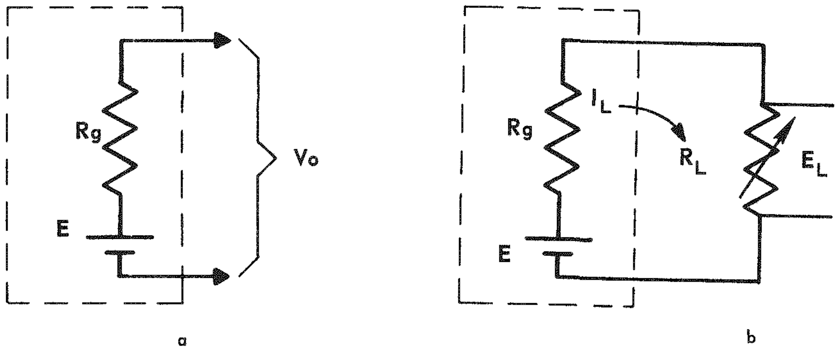


FIGURE 12 - Pressure Burst Capsule



Where E = Generator voltage
Rg = Internal resistance of generator
Vo = Open circuit voltage of generator
R_1 = Optimum load resistance for maximum power output
E_L = Voltage drop across R_L
I_L = Current flow through R_L
Wo = Maximum output wattage in R_L
Ws = Thermal output (watts) of heat source at the time W_o determined
Eff. = Absolute efficiency in percent

FIGURE 13 - Schematic of electrical circuit.

Therefore

$$V_o = E \quad \text{volts}$$

Maximum power is transferred when

$$R_g = R_L \quad \text{ohms}$$

Since the voltage drops around the loop must be equal, then

$$E_L = \frac{E}{2} = \frac{V_o}{2} \quad \text{volts}$$

The power output is

$$W_o = \left(\frac{V_o}{2}\right)^2 \Big/ R_L = E_L{}^2 / R_L \quad \text{watts}$$

The corresponding current flow is

$$I_L = \sqrt{W_o / R_L} \quad \text{amps}$$

The absolute efficiency is

$$\text{Eff} = 100\ W_o / W_s \quad \text{percent.}$$

If several wattages versus load resistance are obtained and plotted, a broad maximum will indicate true maximum wattage which will differ slightly from the single point method described above. This is due to the small Peltier heating and cooling effect on the junctions.

Wattage output of the heat source (W_s) was determined by calorimetric assay to better than ±0.1%.

The Thermal Circuit (Electrical Analogue) The final integrated contract order provided only for the construction of the generators; therefore, no effort was made to determine the actual thermal circuit.

A thermal circuit can be calculated if the following assumptions are made:

- That early measured thermal circuits were correct and based on these since, by ratio calculations, the thermal resistance (Rh, Rc, Rs', Rs'') of the mica card thermopile system can be estimated.

- That the thermal conductivity of Tophel Special-Cupron Special wires is the same as for Tophel-Cupron wires.

The following data on the final prototype generator are required also:

- Heat source wattage

- Details of the thermopile construction, such as dimensions, and physical and electrical constants of the wires are needed to calculate Rt of the actual thermopile. Figure 14 is an electrical analogue based on these conditions. The same system of abbreviations and definitions are used as in Reference 3.

The accuracy of these thermal circuit values can be estimated. Ws is known to ±0.1% by calorimetry techniques. Rt and T_1-T_2 were calculated from physical constants to about ± 10%. The relative small value of Rh and Rc could vary ± 100% and yet cause only a small overall effect. If the foregoing is true, the parallel combination of Rs, Rs', and Rs'' would be about ±10% accurate, but the individual values might vary as much as ± 50%. The total thermal resistance of the generator would be about ± 5%, since its value is dependent primarily on the output of the junctions.

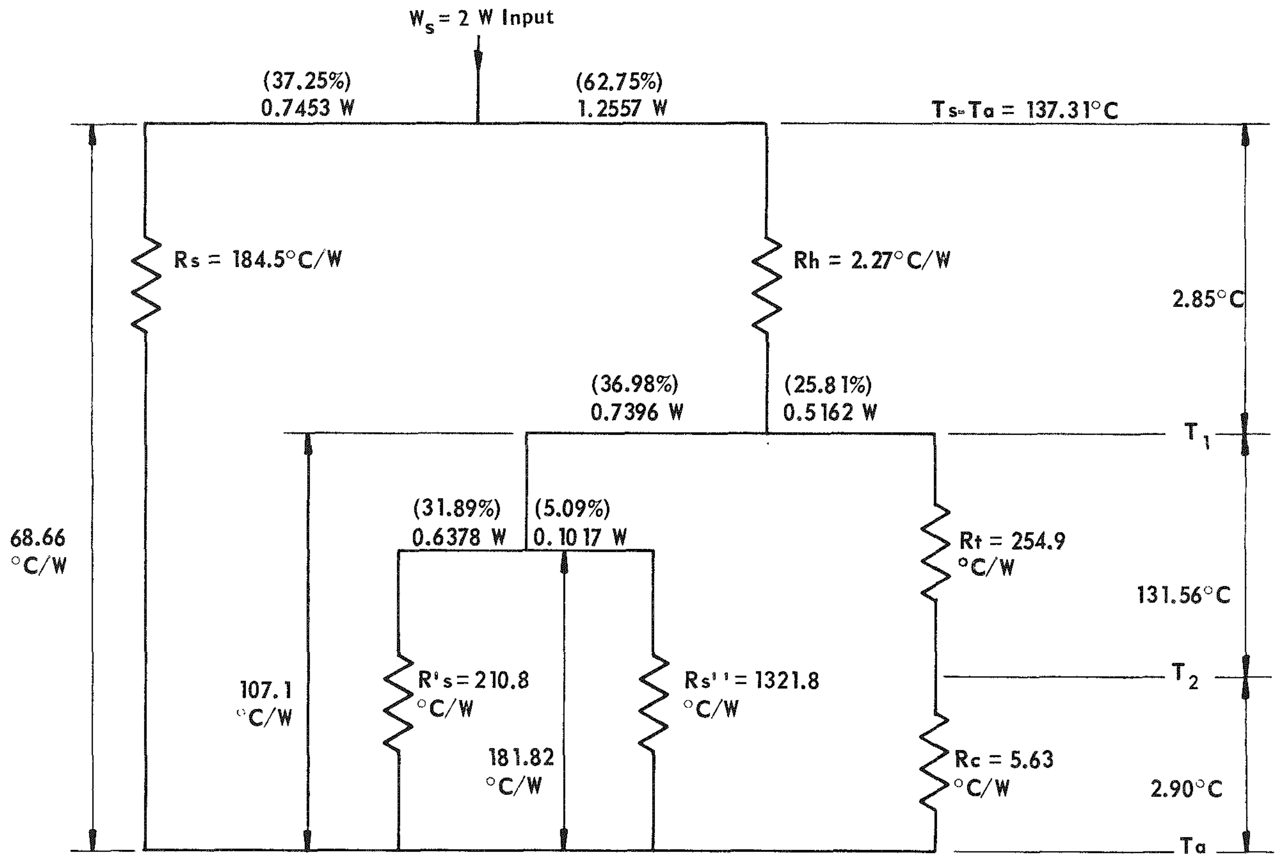


FIGURE 14 - Thermal circuit of generator.

Symbols

T_1	Hot junction temperature (°K)
T_2	Cold junction temperature (°K)
Ts	Source container temperature (°K)
Ta	Ambient temperature (°K)
$(T_1 - T_2)_0$	Temperature drop hot to cold junctions - no load (°C)
Rc	Thermal resistance, cold junctions to ambient ($°C\text{-}W^{-1}$)
Rt	Thermal resistance, hot to cold junctions, of thermocouple materials, adiabatic surface conditions, ($°C\text{-}W^{-1}$)
Rh	Thermal resistance, source container to hot junctions ($°C\text{-}W^{-1}$)
Rs	Thermal resistance, source container to ambients ($°C\text{-}W^{-1}$)
Rs'	Thermal resistance, hot junctions to ambient, which governs the loss of heat from the surface of the thermocouple materials ($°C\text{-}W^{-1}$)
Rs''	Thermal resistance, hot junctions to ambient, which governs the loss of heat, through and from the surface of the mica cards ($°C\text{-}W^{-1}$)
Ws	Source power (W)

Table 2

CHARACTERISTICS OF MILLIWATT GENERATOR

<u>Physical Data</u>

Outside dimensions	- 2.350 in. o.d. x 2.125 in. high
Case material	- Stainless steel - 300 series
Insulation	- Opacified Santocel and argon gas
Mounting screw thread	- 4-40
Weight	- Approx. 2/3 lb or 300 g

<u>Heat Source Data</u>

Inner container	- Tantalum
Outer container	- Haynes alloy No. 25
Approx. bursting pressure (25°C)	- 32,000 psi
Radioactive isotope	- ^{238}Pu
Half-life of fuel form	- ~88.4 yr
Fuel form	- Metal
Fuel weight	- 3.34 to 3.69 g
Thermal power	- 2.0 ± 0.1 W
Maximum 10 yr helium pressure	- Approx. 8100 psi
Useful generator life	- 5 to 10 yr

<u>Radiation from Heat Source</u>

Neutrons at outer surface	- ~10.9 n/cm^2/sec
Gamma at outer surface	- ~7.8 mR/hr

<u>Thermopile Data</u>

Total number of junctions	- 1170 ± 13
Number of mica cards	- 13
Junctions per card	- 90 ± 1
Junctions per inch	- 120
Thermocouple alloy	- Cupron Special-Tophel Special
Thermocouple wire diameter	- 0.0018 in.

<u>Electrical Data</u>

Output Potential

No load	- 11.5 to 12.5 V
45000-ohm load	- 8.5 to 9.5 V

Intermediate tap at 6/13 of output voltage

Table 2 (continued)

<u>Output Power</u>	
With a 16,500-ohm load	- 2.2 mW
With a 45000-ohm load	- 1.8 to 2.0 mW
<u>Total Internal Resistance</u>	
Heat source removed	- ~15,730 ohm
Heat source in place	- ~16,500 ohm

SUMMARY

About 40 ^{238}Pu powered milliwatt generators were built for the primary contractor. The physical and electrical characteristics are summarized in Table 2.

REFERENCES

[1] J.H. Birden, U.S. Patent 2,913, 510 (September 22, 1958).

[2] K.C. Jordan, U.S. Patent 2,844, 639 (November 27, 1959).

[3] B.C. Blanke et al., <u>Nuclear Battery-Thermocouple Type Summary Report</u>, MLM-1127 (January 15, 1962), 68 pp.

[4] S.G. Abrahamson et al., <u>Plutonium-238 Isotopic Fuel Form Data Sheets</u>, MLM-1691 (October 31, 1969), 84 pp.

APPENDIX A

PROPERTIES OF TOPHEL SPECIAL AND CUPRON SPECIAL

Tophel Special is essentially a binary Ni-Cr alloy with about 9.25% chromium by weight. Cupron Special is a binary Ni-Cr alloy with approximately 60% copper, 39.5% nickel, and 0.5% manganese. Cupron Special has the highest known negative thermal emf vs. platinum, and Tophel Special has one of the highest positive thermal emfs vs. platinum. The thermal emfs vs. platinum of these alloys, measured by the Wilbur B. Driver Laboratory, are given in Tables 1 and 2. The data for the combined thermocouple are plotted in Figure 1.

A summary of some physical and electrical properties of Cupron, Cupron Special, Tophel, and Tophel Special is given in Table 3.

The electrical resistivity as a function of temperature of Tophel Special and Cupron Special was measured by H. Chang.[1] These values are given in Tables 4 and 5.

Table 1

THERMAL E.M.F. vs PLATINUM-27 (COLD JUNCTION 32°F)
COMPARED TO THE REGULAR TYPE E COUPLE

Temperature (°F)	(°C)	Tophel Special emf (mV)	Tophel emf (mV)	Cupron Special emf (mV)	Cupron emf (mV)
500	260	+ 8.69	+ 7.97	- 11.58	- 9.98
1000	537.78	+ 18.86	+ 17.51	- 26.31	- 22.55
1200	648.89	+ 22.80	+ 21.26	- 32.41	- 27.77
1500	815.56	+ 28.44	+ 26.72	- 41.56	- 35.58

Table 2

THERMAL E.M.F. vs PLATINUM-27 (COLD JUNCTION 32°F)
COMBINED THERMOCOUPLE OR SINGLE UNIT THERMOPILE

Temperature (°F)	(°C)	Tophel Special vs Cupron Special emf (mV)	Tophel vs Cupron Type E emf (mV)
500	260	20.27	17.95
1000	537.78	45.17	40.06
1200	648.89	55.21	49.03
1500	815.56	70.00	62.30

[1]H. Chang, Energy Conversion, 10, 65 (1970).

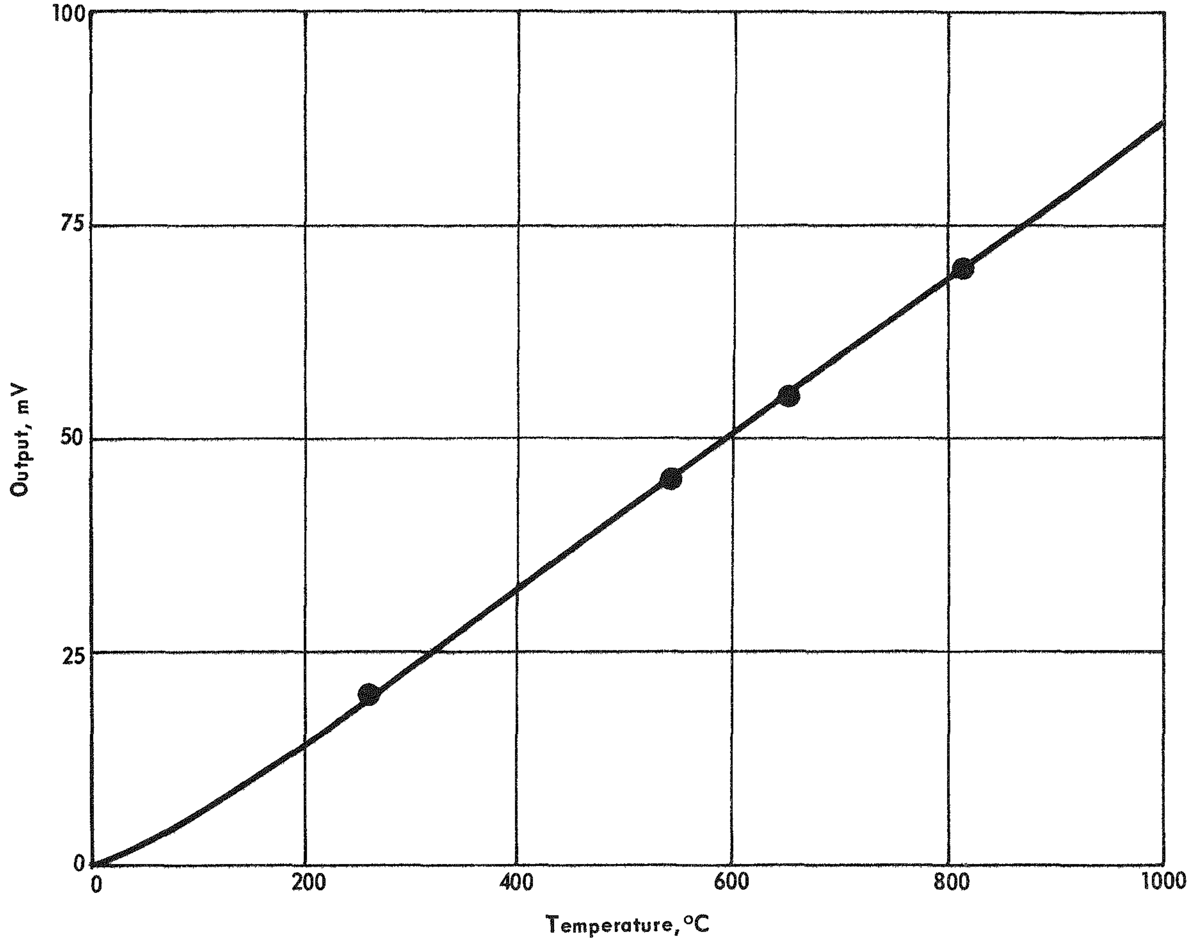


FIGURE 1 - Thermal emf vs. platinum for the combined thermocouple.

Table 3

SUMMARY OF PHYSICAL AND ELECTRICAL PROPERTIES OF THERMOCOUPLE WIRES

Property	Cupron[a]	Tophel[b]	Cupron Special	Tophel Special
Melting Point, °F	2210	2600	2210	2550
Specific Heat (cal/g/°C at 20°C)	0.095	0.11	0.094	0.11
Density (g/cc)	8.90	8.63	8.90	8.63
Resistivity (ohms/circular mil-foot at 20°C)	294	410	270	375
Temp. Coeff. of Resistance (ppm/°C) (20-100°C)	40	390	-85	450×10^{-6}
Thermal Coeff. of Expansion (ppm/°C)	14.9	13.37	14.9	13.37×10^{-6} length/unit length/°C
Yield Strength at 20°C, psi	50,000	30,000	26,000	32,000
Tensile Strength at 20°C, psi	85,000	88,000	45,000	62,000
Percent elongation at 20°C	45	45	30	35

[a]Constantan

[b]Chromel p

Table 4

ELECTRICAL RESISTIVITY OF TOPHEL SPECIAL
AS A FUNCTION OF TEMPERATURE

Mean Temperature T (°C)	Electrical Resistivity $\rho(\Omega\text{-cm}) \times 10^6$	Mean Temperature T (°C)	Electrical Resistivity $\rho(\Omega\text{-cm}) \times 10^6$
36	63.000	419	74.520
45	63.000	500	75.820
50	63.180	517	76.400
50	63.480	542	76.460
68	63.730	555	76.755
69.5	63.800	600	77.580
119	65.670	699	79.380
161	66.980	703	79.465
199	68.000	802	81.000
236	69.060	900	82.980
267	69.820	900	83.268
287	70.123	923	83.430
351	72.245	983	84.400
400	73.870		

Table 5

ELECTRICAL RESISTIVITY OF CUPRON SPECIAL
AS A FUNCTION OF TEMPERATURE

Mean Temperature T (°C)	Electrical Resistivity $\rho(\Omega\text{-cm}) \times 10^6$	Mean Temperature T (°C)	Electrical Resistivity $\rho(\Omega\text{-cm}) \times 10^6$
35	46.017	437	44.086
40	46.017	438	44.086
44	46.017	480	44.086
83	45.374	519	44.406
92	45.694	558	44.406
100	45.051	589	44.406
137	45.051	593	44.406
162	44.730	627	44.729
214	44.730	662	44.729
254	44.406	697	45.051
295	44.086	731	45.051
300	44.086	732	45.374
348	44.086	792	45.694
394	44.086		

APPENDIX B

PREPARATION OF THE LOOSE FILL INSULATION

Santocel® is a silica aerogel. It is free flowing with a density of 5 lb/ft^3. It might produce silicosis if inhaled into the lungs.

Santocel® is transparent to infrared radiation. It can be opacified by the addition of finely ground silicon metal. The silicon metal is purchased 200 mesh and finer. It is ball milled for at least 14 hr for extreme fineness. The Santocel® is screened through a 30 mesh sieve (U. S. Standard) to eliminate large particles. The mixing ratio is 3.6 parts silicon metal to 20 parts Santocel by weight. It is mixed until uniform in color.

It should be slowly heated to 250°F to remove all water vapor, purged with pure argon gas to eliminate all air, and hermetically sealed until used.